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# EXPERIMENTAL STUDY OF VOLTAGE BREAKDOWN CHARACTERISTICS OF TRANSMITTING ANTENNAS

by:

Richard E. Warder, Jr., Richard M. Rosen and Alan S. Penfold

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This research was sponsored by:

Advanced Research Projects Agency
Department of Defense
Project DEFENDER
ARPA Order No. 888

Prepared for:

Air Force Cambridge Research Laboratories
Office of Aerospace Research
United States Air Force
Bedford, Massachusetts [illegible]

Quarterly Technical Report No. 2
Contract No. F19628-68-C-0001
Project No. 8671
Task No. 867100
Work Unit No. 86710001

December, 1967

Contract Monitor
Walter Rotman
Microwave Physics Laboratory

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AFCRL-68-0086 ATD-11-67-043

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ACKNOWLEDGEMENT

This research was supported by the
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# SYNOPSIS

The objective of this program is to evaluate the breakdown characteristics of selected microwave and VHF transmitting antennas under both ambient (cold air) and simulated reentry (plasma sheath including ablation effects) conditions at high altitude. The purpose of the program is to provide experimental data which will aid in selection of reentry jammers. The power-handling capabilities, the pattern of the radiated fields, and the input impedance of selected antennas which are compatible with the geometry of a conical reentry vehicle are to be determined.

The modifications of the basic test cone model to accommodate additional plasma diagnostic instrumentation are described and the results of measurements of the radiation pattern of the X-band slot antenna/model configuration under free-space and anechoic chamber conditions are presented. Tests of the microwave and diagnostic instrumentation in the plasma tunnel are described and the design/fabrication status of the VHF antenna electrical instrumentation is reported.

AUTHORS'

ACKNOWLEDGEMENT

The authors wish to acknowledge many helpful discussions with: D.L. Curtis, G. Fonda-Bonardi, Dr. G.R. Seemann and Dr. J.A. Thornton during the course of this research.

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# 1. INTRODUCTION

This report describes the work performed by the Space Sciences Laboratories of Litton Systems, Inc., during the second quarter of Contract F19628-68-C-0001 for the Air Force Cambridge Research Laboratories under ARPA Project DEFENDER, ARPA Order No. 693.

The objective of this program is to evaluate the breakdown characteristics of selected microwave and VHF transmitting antennas under both ambient (cold air) and simulated reentry (plasma sheath including ablation effects) conditions at high altitude. The purpose of the program is to provide experimental data which will aid in selection of reentry jammers. The power-handling capabilities, the pattern of the radiated fields, and the input impedance of selected antennas which are compatible with the geometry of a conical reentry vehicle are being studied.

No single experimental facility can properly simulate the combination of fluid dynamic and electromagnetic phenomena that are relevant to the problems of reentry jammers.[1] The approach taken in the present program utilizes the steady-state operation and large size flow field afforded by the Litton electrodeless MHD accelerator to make detailed measurements of antenna breakdown characteristics. Although reentry conditions cannot be duplicated completely, it is possible to determine the antenna radiation characteristics as affected by a known plasma environment; i.e. one which can be investigated by detailed diagnostics.

During the present reporting period, the technical effort was concentrated on: modifying the basic test cone model to accommodate additional plasma diagnostic instrumentation; measurements of the radiation

pattern of the X-band slot antenna/model configuration under free-space and anechoic chamber conditions; testing of the microwave and diagnostic instrumentation in the plasma tunnel; and preparation of the VHF antenna electrical instrumentation.

## 2. BASIC TEST STRUCTURE

The approach taken in the present program is to perform the antenna experiments in a well-known plasma environment. Accordingly, the measurement of the plasma parameters associated with the boundary layer over the test cone constitutes an important facet of the program.

The presence of diagnostics for probing the spatial variations of the boundary layer plasma will perturb the measurement of antenna radiation patterns. Accordingly, it is necessary to obtain the plasma properties separately from the antenna data. This requires that the plasma flow over the test cone must be reproducible and the index of reproducibility must rely upon diagnostics located on the cone surface.

The basic test model consists of a 6°20' semivertex angle cone approximately 36 inches long connected to a hollow cylindrical afterbody.[1] This model, fabricated during the first quarter, was modified to accommodate additional plasma diagnostic instrumentation. The additional diagnostics consist of an impact pressure port and a double Langmuir (electrostatic) probe located at the nose of the cone. The choice of these two particular sensors is based on previous measurements[1, 2] which indicate that the impact pressure and the electron density are quite sensitive indices of the plasma flow conditions. The modified test model is shown pictorially in Figures 1 and 2 and schematically in Figure 3.

The diagnostic instrumentation located on the cone consists of: three double electrostatic probes; four static pressure ports; an impact pressure port, and a thermocouple for surface temperature measurements.

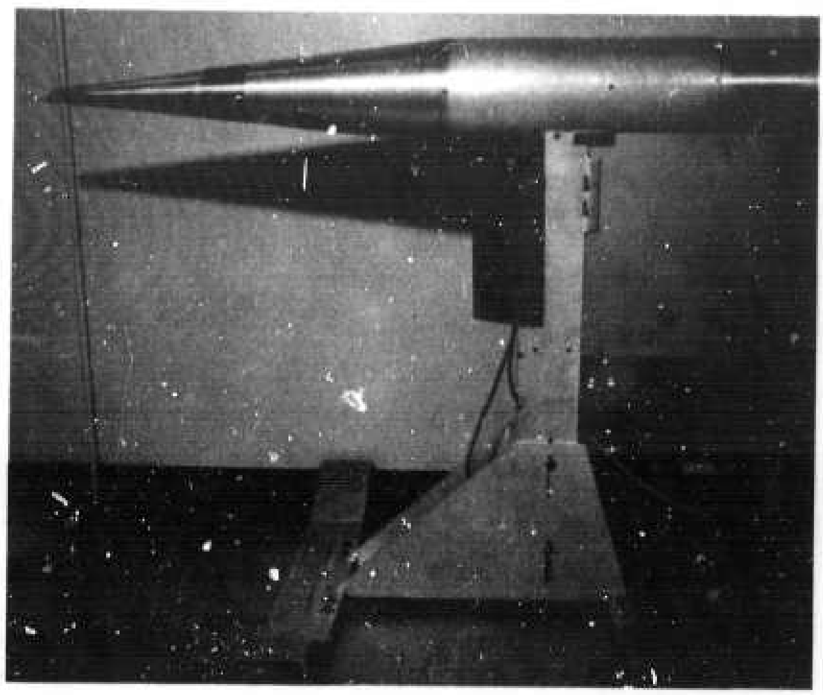


Figure 1. Photograph of Modified Test Model Assembly

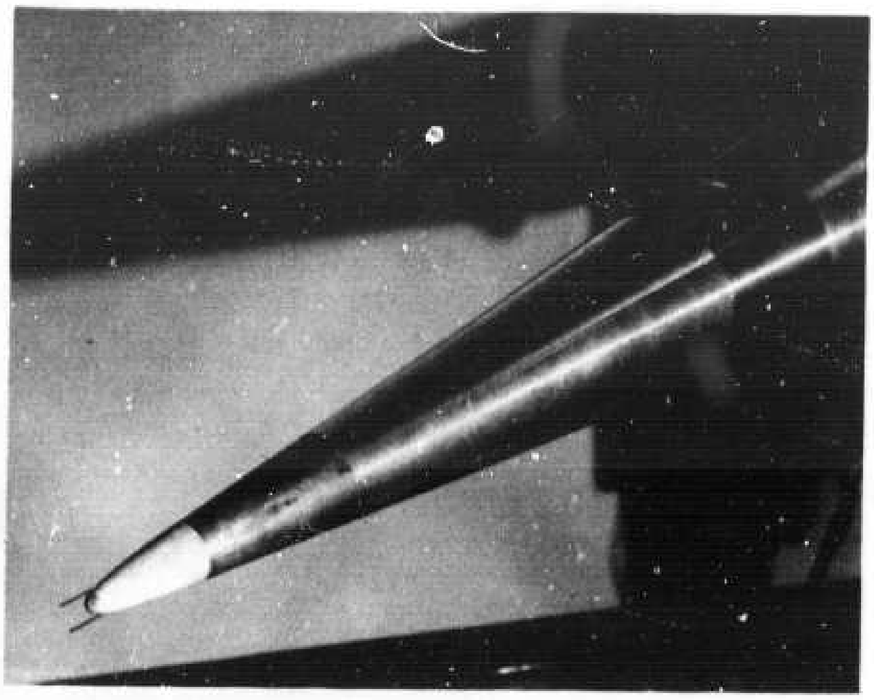


Figure 2. Close-Up of Slot Antenna and Nose Langmuir Probe

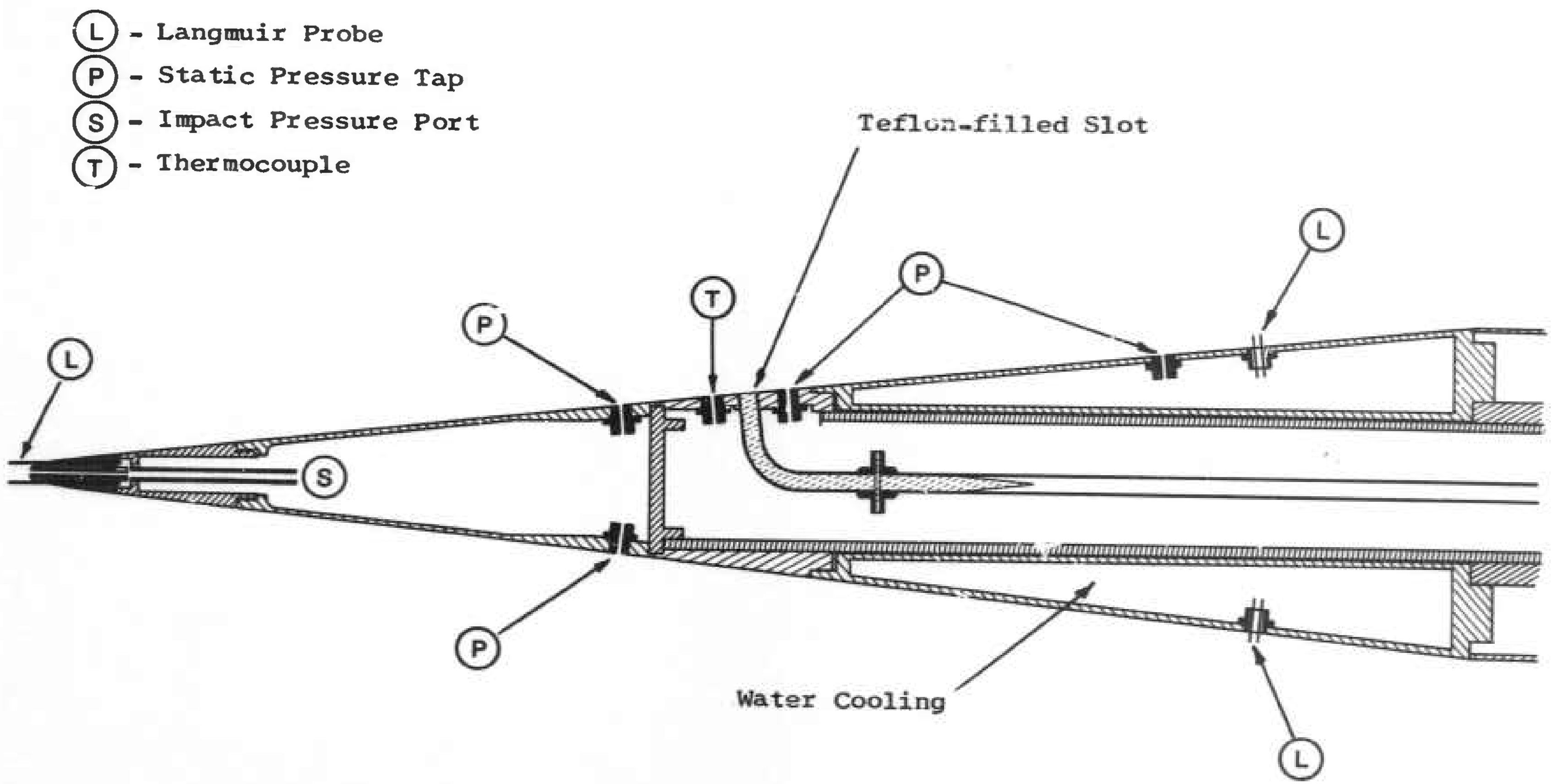



Figure 3. Schematic of Test Cone

A relatively simple interpretation of the Langmuir probe data in terms of electron density and electron temperature requires that certain relations between the probe electrode size, the mean free path, and the Debye length be satisfied. A fixed geometry probe (of reasonable dimensions) cannot satisfy these relations when used over a wide range of electron densities (as in the present program). The choice of probe size and spacing was therefore primarily dictated by considerations of ruggedness and ease of fabrication.

The Langmuir probe located at the nose of the cone has cylindrical tungsten electrodes (0.040 inches in diameter and 0.65 inches long) with 0.5 inch spacing. The two Langmuir probes located near the rear of the cone are used to indicate the azimuthal symmetry of the electron density distribution. These probes which were also included so as to provide indices of the flow conditions, rather than as primary diagnostic information, have cylindrical tungsten electrodes 0.040 inches in diameter and 0.25 inches long. The electrodes are spaced 0.125 inches apart by a boron nitride insulator. The two probes are located at the same axial station but 180° apart in azimuth on the cone surface.

The impact pressure sensing hole is 0.063 inches in diameter and is located between the electrodes of the nose Langmuir probe as indicated in Figure 3. The impact pressure is sensed by a Veeco DV 4 AM thermocouple gauge.

Four surface pressure ports are used to measure axial and azimuthal variations in the static pressure at the cone surface. The pressures are sensed by Veeco DV 1 AM thermocouple gauges. The cone surface temperature is determined by an iron-constantan thermocouple in a 0.040 inch diameter stainless steel jacket which in turn is press-fitted into a brass plug threaded into the cone wall.

Figure 3 shows schematically the location of the various sensors on the cone surface.

## 3. RADIATION PATTERN MEASUREMENTS

Measurements were made of the radiation patterns of a Teflon-filled X-band slot with an aperture measuring 0.4 by 0.9 inch, located on the nose cone. The receiver was a DBG-520 horn mounted on a traversing mechanism as shown in Figure 4. The traversing mechanism, which will be exposed to relatively high temperatures, was constructed of non-metallic materials such as glass-loaded Teflon and phenolics to minimize perturbation of the radiation field. The metallic drive motors and chains and sprockets are located at the top of the vacuum chamber behind the anechoic material as indicated in Figure 5.

The receiving horn is located in the far field of the slot antenna. A thermistor is attached to the horn and protected from low pressure effects[1] by a vacuum seal. The receiver power is read directly on a Hewlett-Packard 430C power meter. An earlier plan to make a transition at the horn from waveguide to coaxial cable was found to suffer from intolerable reduction in received power due to losses in the long length of coaxial cable.

Measurements were made of the E and H-plane patterns of the X-band slot both in an outdoor antenna range and in an indoor anechoic chamber with the same size and configuration as the vacuum chamber. This latter setup allows determination of the influence of metal objects which are located within the plasma tunnel vacuum chamber. Figure 6 shows the test cone located in the anechoic chamber.

E-plane radiation pattern measurements, both in and outdoors of the anechoic chamber, were made by traversing the receiving horn axially

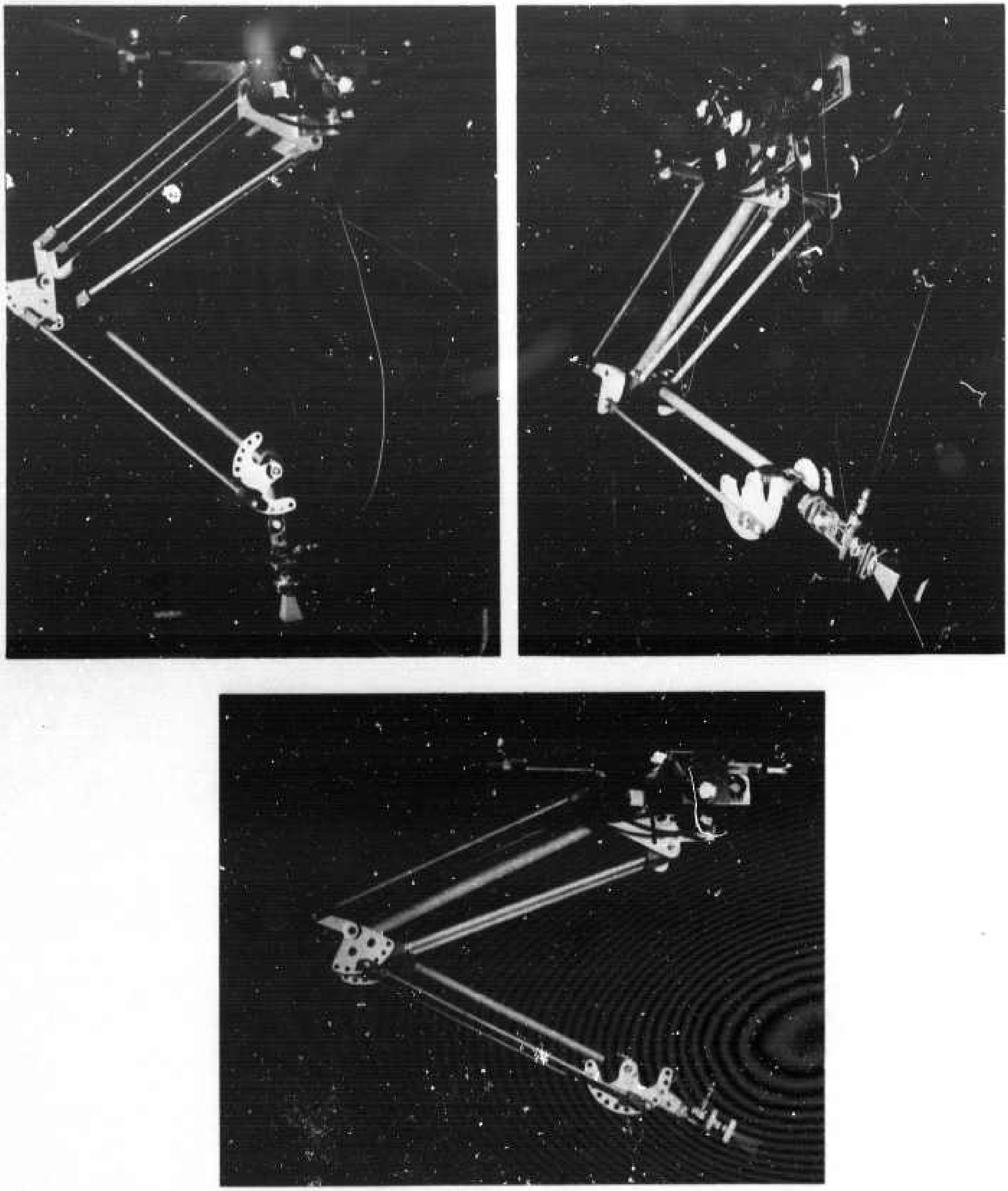


Figure 4. Antenna Sensor Traversing Mechanism

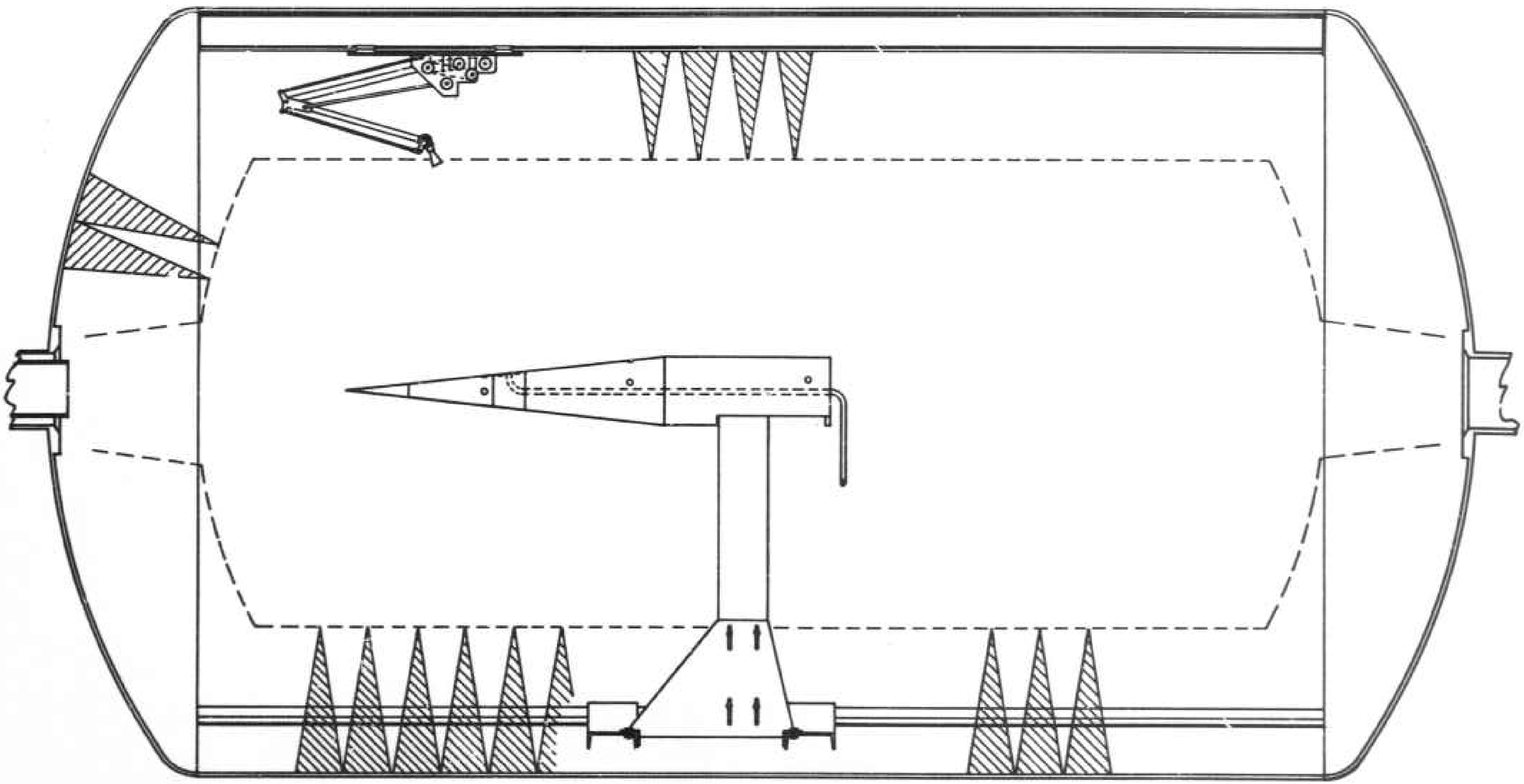


Figure 5. Side View of Test Chamber and Model Layout

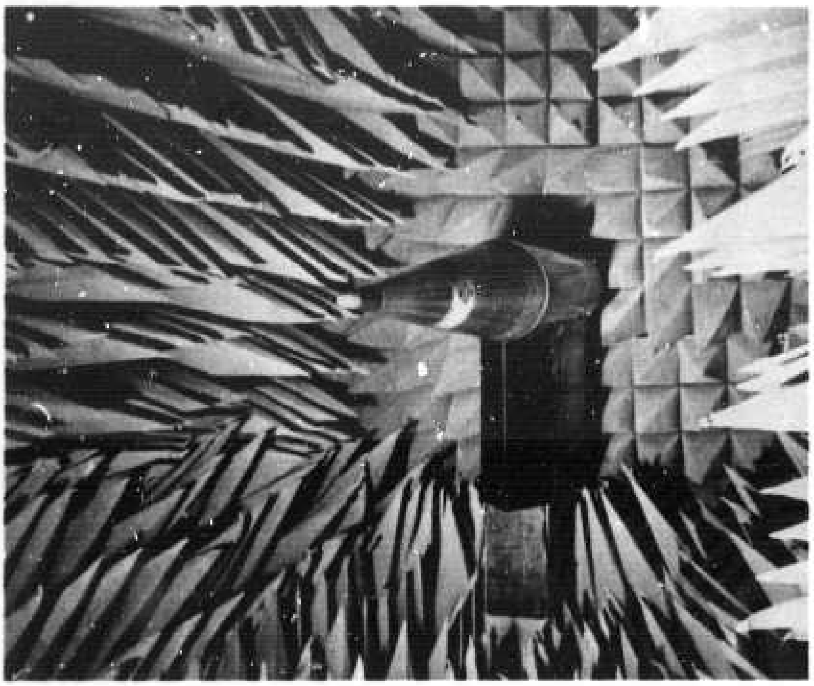


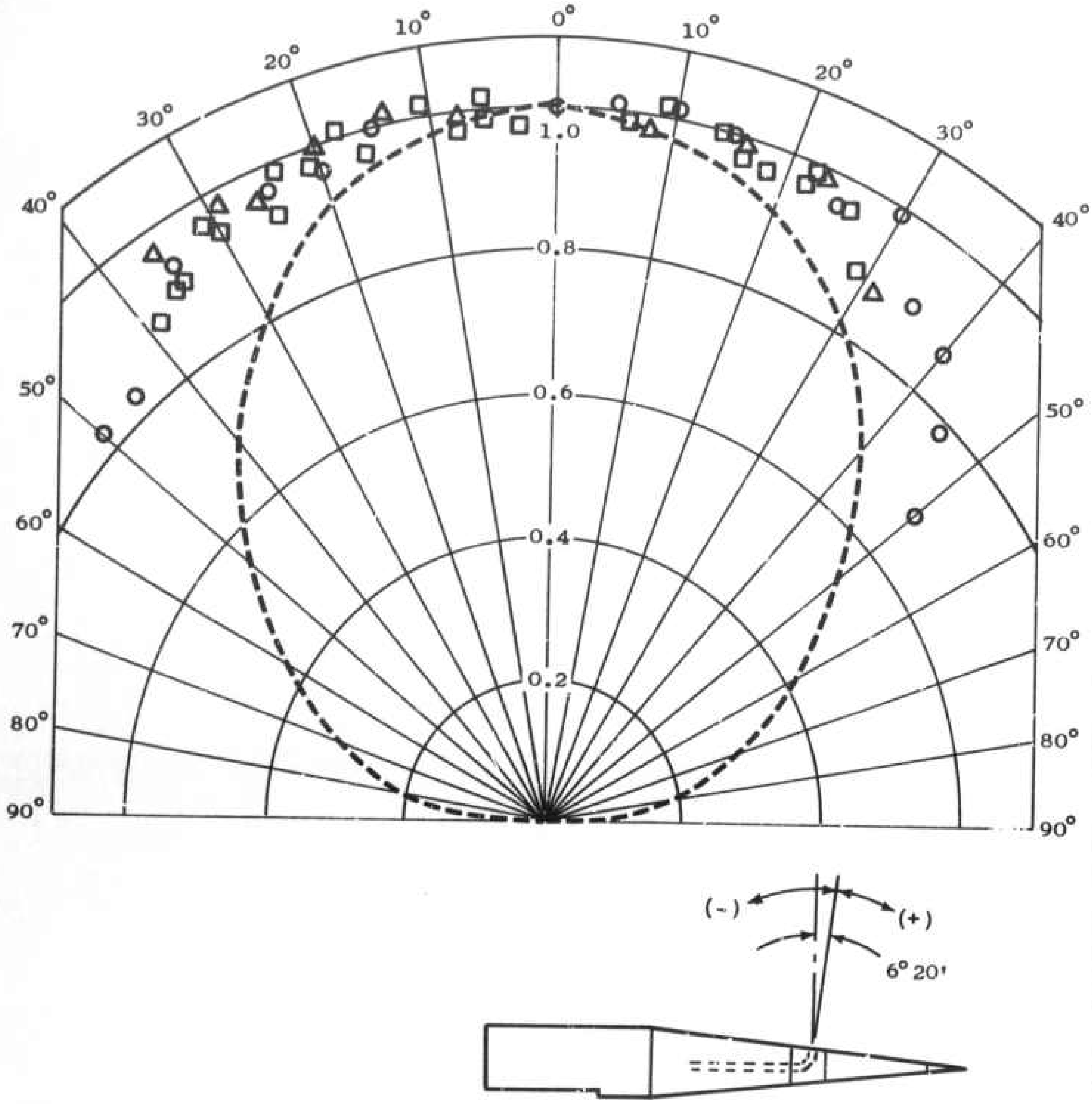
Figure 6. Test Model in Anechoic Chamber

a beam located above and colinear with the test model. The receiving horn was manipulated so as to always point toward the slot antenna. This orientation was accomplished by use of the tilting capability built into the traversing mechanism. The results of the E-plane pattern measurements are compared in Figure 7 and indicate that there is no substantial difference between the patterns taken outdoors and those taken in the indoor anechoic chamber. The solid curve shown in Figures 7 and 8 are the E and H-plane radiation patterns respectively of an open-ended X-band waveguide as given by Southworth.[3]

Measurements of the H-plane radiation patterns, both outdoors and in the anechoic chamber, were made by rotating the cone and slot antenna about the cone axis with the receiving horn located at a particular axial station. Although measurements were taken at a number of axial stations, the majority of measurements were taken of the principal H-plane pattern, i.e. $\theta = 0°$ as shown in Figure 7. The results of these measurements are shown in Figure 8 and indicate that the patterns taken outdoors and those taken in the anechoic chamber are sufficiently consistent.

At the X-band operating frequency of 9.225 kMc, it is possible for higher order modes to propagate in the Teflon-loaded guide. Inspection of the measured radiation patterns indicates however that negligible, if any, power is carried in higher order modes.

A large metallic (approximately 6 feet by 6 feet) heat exchanger or "gas catcher" is located in the rear of the vacuum test chamber. The purpose of this catcher is to cool the plasma beam prior to pumping by the vacuum system. The influence of the gas catcher on the antenna patterns was simulated in the anechoic chamber. Antenna patterns taken with the stimulated gas catcher in place are also shown in Figure 7 and 8 and indicate that the presence of the gas catcher should not affect antenna radiation pattern measurements.



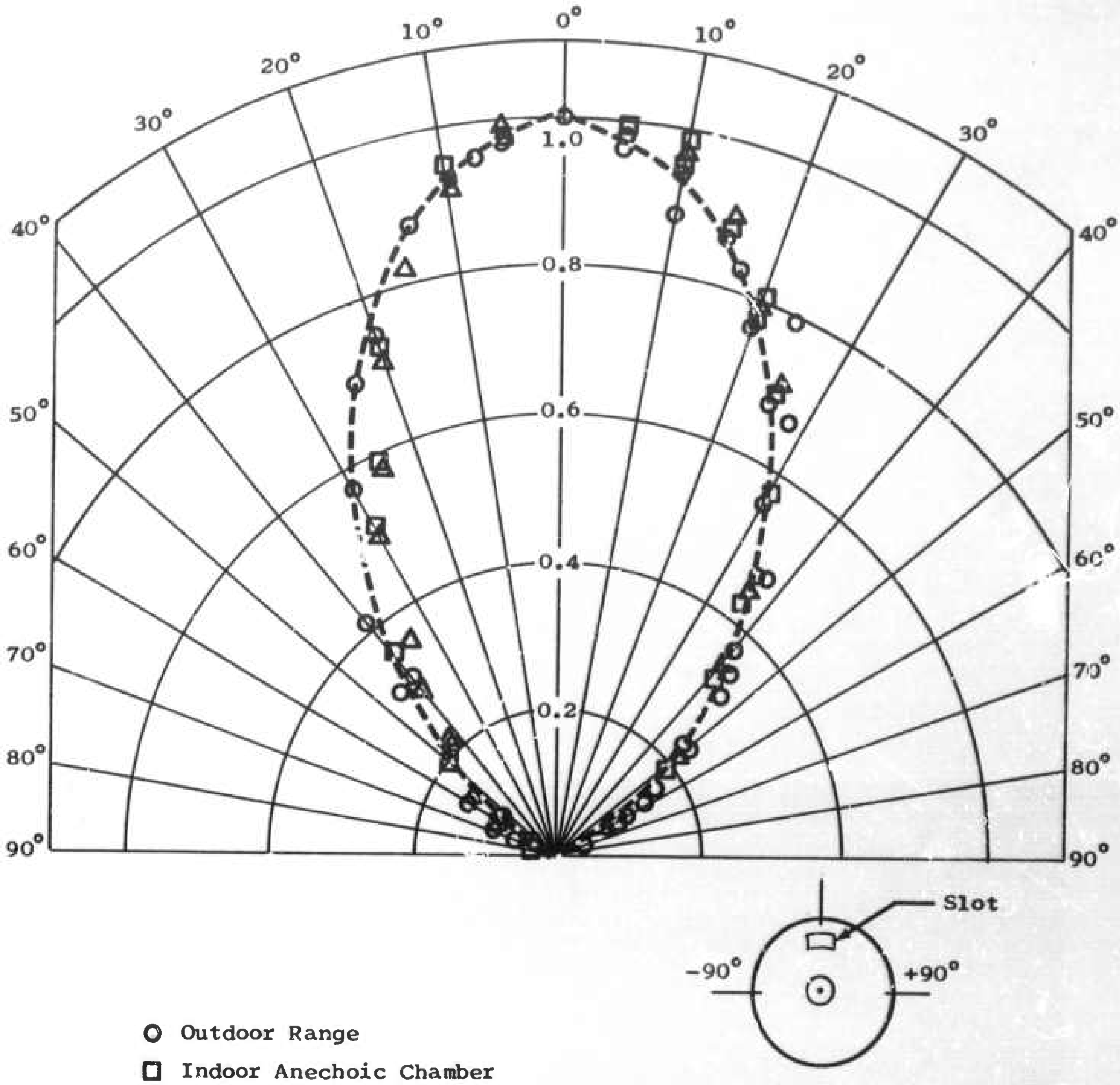

O Outdoor Range

□ Indoor Anechoic Chamber

△ Indoor Anechoic Chamber - Simulated Gas Catcher

— — E-plane pattern Of Open-Ended Slot - After Southworth

Figure 7. E-Plane Radiation Pattern Of X-Band Slot




O Outdoor Range

□ Indoor Anechoic Chamber

△ Indoor Anechoic Chamber - Simulated Gas Catcher

-- H-plane Pattern Of Open-Ended Slot - After Southworth

Figure 8. H-Plane Radiation Pattern of X-Band Slot

The outside of the anechoic chamber was covered with aluminum foil and the antenna pattern measurements were repeated. The purpose of this test was to simulate the metal walls of the plasma facility test chamber and patterns taken under these conditions were the same as those taken in the absence of the aluminum foil covering. These results verify that the anechoic material will be quite effective in eliminating reflections of electromagnetic energy from the metal test chamber walls.

It might be expected at X-band wavelengths (~3 cm.) that the anechoic material would not be necessary due to the large separation between the slot antenna and the vacuum chamber walls. This supposition was checked by lining approximately 75 percent of the inside cylindrical section of the anechoic chamber with aluminum foil and repeating the antenna radiation pattern measurements. Comparison of the results obtained for the two conditions showed that there was typically a minimum of 10 percent difference in the received power. This indicates that the reflection of electromagnetic energy from the walls is important even with the small wavelength and large chamber size employed in the present experiment and that proper precautions must be taken to eliminate just such reflections.

# 4. PRELIMINARY TESTS IN PLASMA TUNNEL

Basic structure tests and microwave measurements were conducted in the plasma tunnel to check the suitability of the basic test structure, to calibrate and assess the performance of the associated diagnostic instrumentation and to test microwave instrumentation.

The basic structure tests included: evaluation of the various pressure sensors; a series of measurements of electron density using the Langmuir probes; and evaluation of the performance of the cone rotation mechanism under high temperature, low pressure conditions.

The microwave measurements were made to delineate any potential problem areas and identify any particular phenomena that might require more attention than originally planned. The tests included measurements of the breakdown and extinguish power for the X-band slot and determination of the antenna power reflection coefficient for certain selected conditions.

## 4.1 Basic Test Structure Tests

The tests of the cone diagnostic instrumentation consisted of a series of measurements with and without plasma flow. During these tests the gas composition (pure argon and argon/air mixtures) and the power input to the plasma accelerator were varied over a sufficiently wide range to cover the conditions to be used during the detailed testing program. Figure 9 shows the cone in an argon plasma flow. The cone is located at an axial station such that the nose tip is approximately two feet downstream of the accelerator exit. Measurements were made of the impact pressure, axial and azimuthal pressure gradients and of the

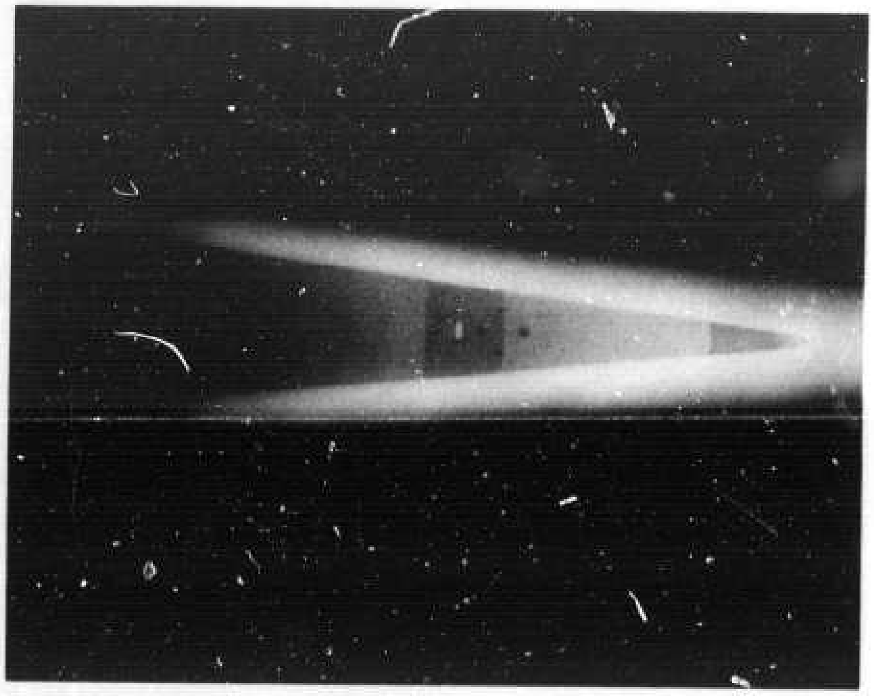


Figure 9. Plasma Flow over Cone

azimuthal symmetry of the ionized component of the flow over the cone using Langmuir probes mounted on the model.

The impact pressure measurements together with a knowledge of the static pressure were used to determine the free stream Mach number. The Mach number was found to be approximately 0.6 based on an assumed ratio of specific heats, $\gamma$, of 1.67. (Calculations show that for $M<0.7$ the error in using a different value of $\gamma$, such as 1.4, for example, is negligible.)

An additional feature afforded by the impact pressure port is the ability to inject seed material at the cone tip. Figure 10 shows, for example, how air injected at the stagnation point quenches the luminosity (and also the electron density) as produced by the same accelerator operating conditions without air injection as shown in Figure 9.

The measurements of static pressure at the locations shown schematically in Figure 3 indicated no observable azimuthal or axial variations in the surface pressure for all the plasma flow conditions employed. This result is not surprising inasmuch as the subsonic flow over a properly aligned slender cone should not cause large pressure gradients.

The major portion of the diagnostic instrumentation testing was devoted to the evaluation of the three Langmuir probes located on the cone surface as indicated in Figure 3. The evaluation of the probes was concentrated on obtaining electron density information as well as assessing the durability of the probes when subjected to high temperature plasma flow for extended periods of time.

The Langmuir probe located at the nose of the cone is used as an index of the free stream electron density while the two probes located on the aft portion of the cone were used to determine the symmetry of the ionized component of the flow over the cone surface.

During the initial tests, all three probes gave spurious data. These effects were manifested as atypical current-voltage characteristics

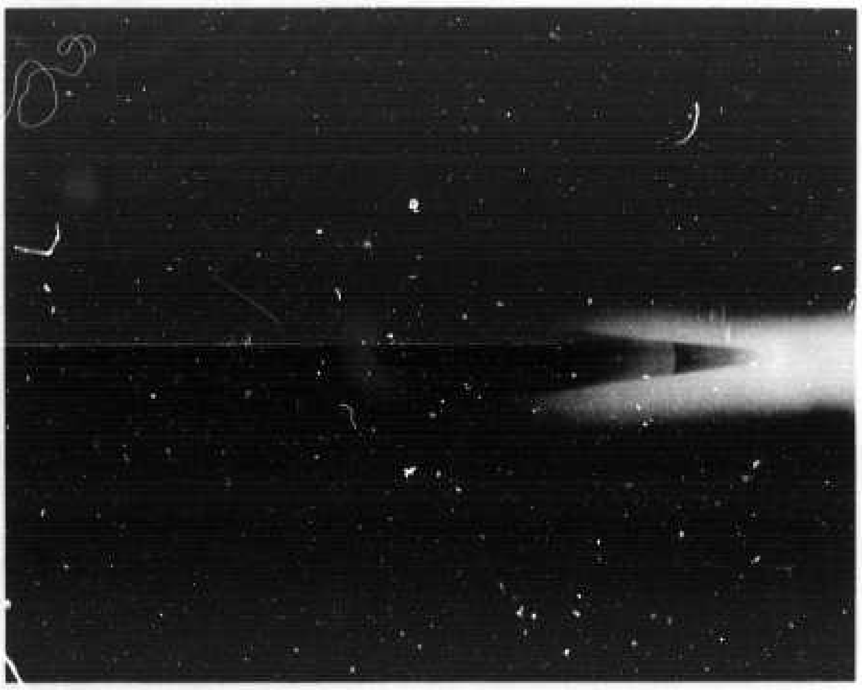


Figure 10. Plasma Flow over Cone with Air Injection at Stagnation Point

and it was impossible to obtain reproducible data. Previous experience in this laboratory has shown that care must be exercised to avoid contamination of the probe electrodes. The probe electrodes were polished with emery cloth and this treatment was found to be successful in eliminating the spurious behavior of the two probes located on the rear portion of the cone.

The data obtained with the Langmuir probe located on the nose of the test cone was particularly erratic. This probe is exposed to the most severe temperatures and also is not as well cooled due to its particular construction. It was observed that, as the probe was exposed to the plasma beam for an extended period of time, a dark deposit formed on the boron nitride surface at the base of one of the electrodes. This deposit was found to be electrically conducting and thereby increased the effective current collecting area of that particular electrode. Indeed, probe data taken with this deposit present exhibited the asymmetrical current-voltage characteristic typical of a single probe rather than the symmetrical (if the probe electrode areas are equal) double probe trace.

It was suggested that this deposit might be due to material eroded from the accelerator channel. This hypothesis was checked by covering the two probe electrodes with a piece of boron nitride and exposing this assembly to the plasma beam for approximately 30 minutes. The conducting deposit was not observed on the boron nitride cover and it is believed that the deposit was the result of treatment by the plasma beam of residual oils left from the fabrication processes. The deposit was removed from the boron nitride surface by polishing and the probe was subsequently performed satisfactorily in all respects.

The tests of the symmetry of the ionized flow over the test cone were made using the two Langmuir probes located 180° apart on the rear portion of the cone. It is possible to interchange the relative positions of the two probes using the rotation capability built into the cone and thereby eliminate dissimiliarities in probe construction as a factor

from any differences obtained in the Langmuir probe data at a particular azimuthal location. Evaluation of the probe responses using this procedure showed that the two probes yielded identical current-voltage characteristics when exposed to the same plasma flow conditions.

These tests also permitted evaluation of the rotation mechanism under high temperature, low pressure conditions. The rotation mechanism performed satisfactorily under all test conditions.

After it was established that the probes were performing properly, a series of measurements of the flow symmetry over the cone were made. The ability to determine the flow asymmetry over the cone was quite satisfactory in that measurements with the Langmuir probes, which yield essentially an electron density determination, were corroborated by visual and photographic observations. The cone was deliberately misaligned in the plasma flow and the resultant asymmetries were readily detected. In summary, the Langmuir probes have been found to be a quite sensitive index of the flow symmetry over the test structure.

## 4.2 Microwave Instrumentation Tests

A number of preliminary measurements were made using the microwave instrumentation. These measurements included no-flow cold air breakdown and extinguish powers as a function of the ambient pressure and determinations of the reflected power before and after breakdown in no-flow cold air and also with plasma flow.

Previously no-flow cold air tests had been conducted of the breakdown characteristics of a Teflon-filled X-band (RG-52/U) waveguide aperture located in a 4-inch square ground plane.[1] These tests were conducted in a small Pyrex chamber and with a section of waveguide approximately 5 feet long separating the magnetron and the aperture. One of the objectives of the present series of tests was to determine if any gross differences existed due to the slight change in geometry (from a square ground plane to a conical nose acting as a conducting plane) and also the

effect of the greatly increased length of waveguide between the magnetron and the nose cone (a change from approximately 5 feet to approximately 30 feet).

In addition to the longer length of waveguide which results in increased attenuation of the incident power, the electrical continuity of the waveguide system is broken at a point approximately one foot before the cone by a thin Teflon sheet. This is necessary to prevent d.c. current flow from the plasma to ground through the waveguide (i.e. to prevent the waveguide from acting like one electrode of a Langmuir probe.)

Because the incident power is measured at the magnetron rather than at the slot, the losses of the waveguide system must be taken into account to properly present the data. These losses will be included in future tests by comparing the incident power measured at the magnetron with that measured at the slot by use of a directional coupler and average power meter.

The experimental results of the cold air, no-flow breakdown studies are shown in Figure 11. The breakdown power is taken to be that incident power at which the reflected power increases abruptly. This also coincides with the sudden appearance of luminosity at the slot aperture. The breakdown powers have not been corrected for waveguide effects. The pressure range covered represents an equivalent altitude change of from approximately 100 to 200 kilofeet. Also shown for comparison are the previous experimental results for the Teflon-filled aperture in the 4-inch square ground plane[1] and the results of Scharfman[4]. The Teflon-filled slot on the cone consistently requires more power for breakdown than the aperture in the square ground plane except for the data taken at the two highest pressures.

After breakdown had occurred and a plasma was visible over the aperture, further increases in power resulted in an increase in the area of the aperture covered by the plasma. This result is consistent with previous observations.[5]

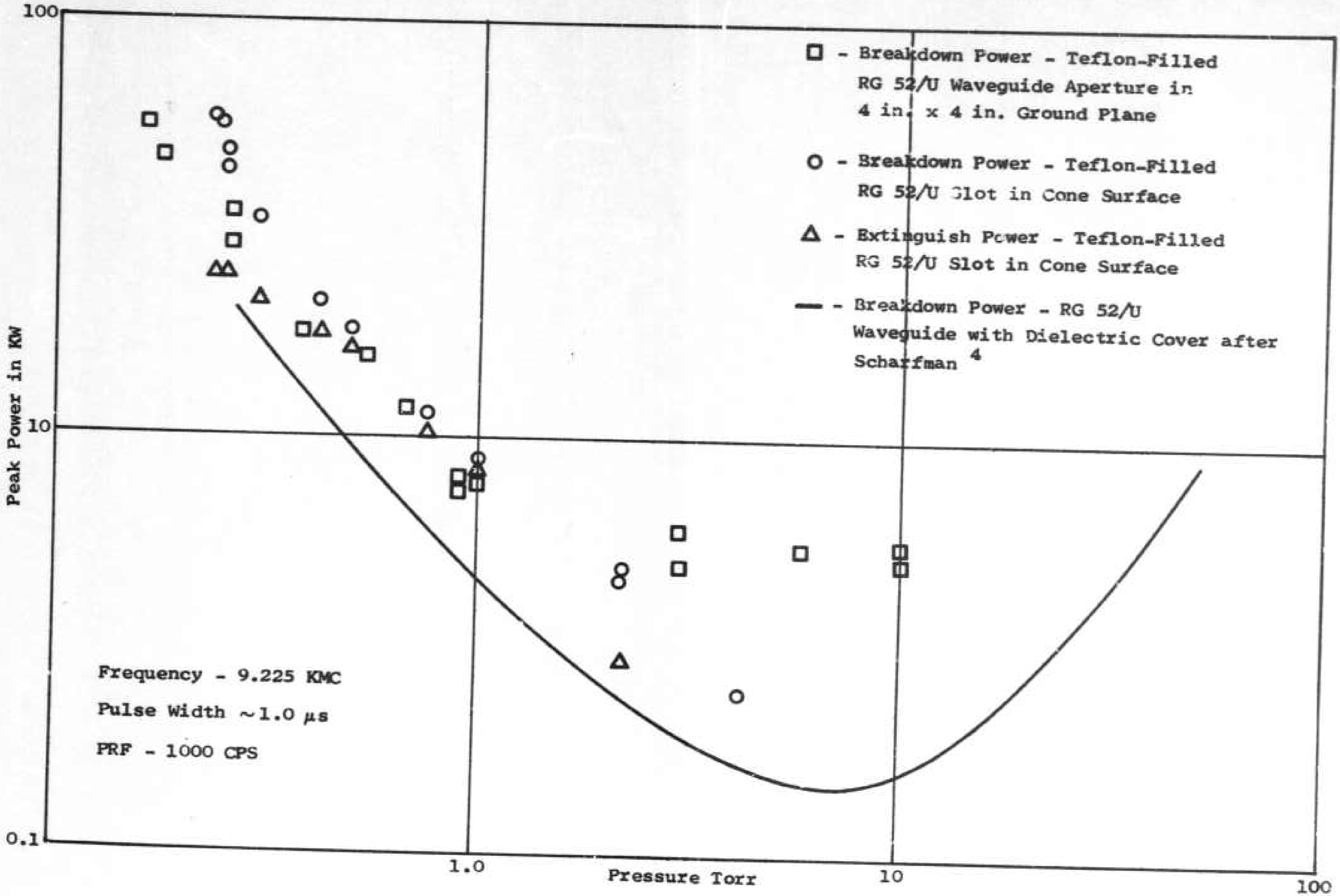



Figure 11. Cold Air Breakdown Characteristics of X-Band Slots

Typical experimental cold air, no-flow results obtained from measurements of the reflected power are shown in Figure 12. The incident power is that required for breakdown at the particular pressure and the reflected power is that measured with the slot broken down by this incident power. The pressures and peak powers correspond to the experimental conditions given in Figure 11.

The proper inclusion of the effects of the long length of waveguide will be particularly important in measuring the reflection coefficient inasmuch as the reflected signal undergoes the same amount of waveguide loss as the incident signal. The magnitude of this effect can be seen from the fact that an experiment in which the slot was tightly covered with aluminum foil to simulate a reflection coefficient of unity gave a power reflection coefficient of approximately 0.4.

The variation in reflected power with either an increase or decrease in incident power after breakdown had occurred was not studied in detail in these particular tests.

When a plasma flow was present, there was no sharply defined breakdown as manifested by a sudden increase in reflected power for example. Rather, as the incident power was increased, the reflected power increased smoothly and at some point during this sequence additional luminosity would be observed at the slot. There was no correlation between the onset of luminosity and the reflected power.

It is interesting to note that the reflection coefficient was significantly greater when there was plasma flow over the cone. A typical experimental point is shown in Figure 12. Whether this is due to a sufficiently high electron density in the plasma flow, such that the plasma is overdense, is not known. However, these effects will be systematically studied during the detailed testing program currently in progress. In particular, special attention will be given to the determination of meaningful breakdown criteria in the presence of a plasma flow.

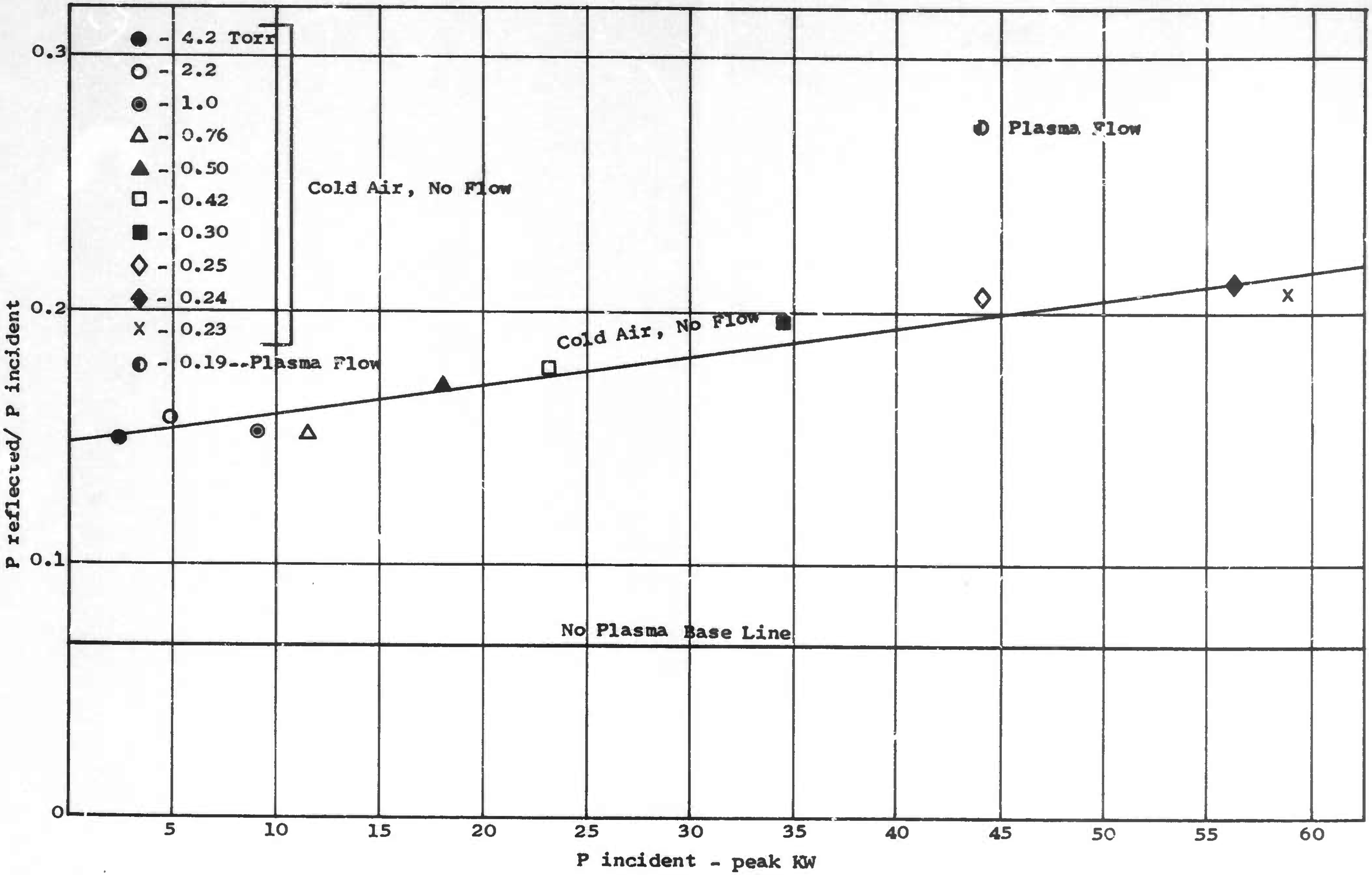



Figure 12. Power Reflection Coefficient of Slot Under Breakdown Conditions

# 5. VHF ANTENNA TESTING

## 5.1 VHF Antenna Selection

The selection of the VHF antenna to be tested during the second half of the program is based on utilizing to the fullest extent possible advances in the technology of VHF antenna design that are occurring. Thus, the study of an actual VHF jamming antenna is the most meaningful for the purpose of the present program.

The original antenna selected for testing is that currently being studied by Cornell.[6] In response to technical direction, a substantially improved version of this type of antenna[7] was selected for testing in the Litton facility. At the present time detailed construction drawings of the antenna and data on its electrical characteristics are being obtained in order to initiate construction of the antenna structure.

## 5.2 VHF Electrical Instrumentation

The power source for the VHF experiments will be an "in house" fabricated 2Kw, balanced output, linear amplifier driven by a surplus 50 watt transceiver. During the previous quarter, the linear amplifier was designed and fabricated. This assembly is currently being tested.

The breakdown and extinguish powers for the VHF antenna will be determined from a measurement of the power on a Hewlett-Packard 430C power meter that is coupled to each of the main lines of the balanced output through a high power calibrated coaxial directional coupler and attenuator. During the previous quarter, the high power directional couplers were procured and are currently undergoing performance tests.

The VHF antenna input impedance will be measured using standard slotted line techniques. Two coaxial/slotted lines with the capacity to handle the high power levels anticipated were designed and construction initiated. The slotted lines will also be used to provide a convenient phase reference for measurements of the transmitted field components inasmuch as the VHF antenna testing will be restricted to near-field measurements by the dimensions of the wind tunnel, and the particular VHF wavelength utilized.

Details of the particular constructions of these components and their arrangement will be deferred until the next reporting period where they can be discussed within the context of more complete experimental data.

## 6. THIRD QUARTER PLANNED ACTIVITIES

During the third quarter, the experimental effort will concentrate on completion of the studies of the X-band slot/cone model configuration and analysis of the resultant test data.

Fabrication and testing of the VHF electrical instrumentation will be completed and the fabrication of the VHF antenna will be initiated.

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Unclassified

Security Classification

**DOCUMENT CONTROL DATA - R&D**

*(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)*

| | |
|---|---|
| 1. ORIGINATING ACTIVITY (Corporate author)<br>Litton Systems, Inc.<br>Space Sciences Laboratories<br>336 N. Foothill Road, Beverly Hills, California | 2a. REPORT SECURITY CLASSIFICATION<br>Unclassified<br>2b. GROUP<br>NA |

3. REPORT TITLE

EXPERIMENTAL STUDY OF VOLTAGE BREAKDOWN CHARACTERISTICS OF TRANSMITTING ANTENNAS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Scientific. Interim.

5. AUTHOR(S) (Last name, first name, initial)

Richard C. Warder, Jr.
Richard M. Rosen
Alan S. Penfold

| 6. REPORT DATE | 7a. TOTAL NO. OF PAGES | 7b. NO. OF REFS |
|---|---|---|
| December, 1967 | 33 | 7 |

| | |
|---|---|
| 8a. CONTRACT OR GRANT NO.<br>F196828-68-C-0001 ARPA Order No. 693<br>b. PROJECT NO.<br>Project, Task, Work Unit Nos.<br>8671-00-01<br>c. DoD Element 6.25.03.01.R<br>d. DoD Subelement n/a | 9a. ORIGINATOR'S REPORT NUMBER(S)<br>ATD-11-67-043<br>Quarterly Technical Report No. 2<br>9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)<br>AFCRL-68-0086 |

10. AVAILABILITY/LIMITATION NOTICES

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| 11. SUPPLEMENTARY NOTES This research was sponsored by the Advanced Research Projects Agency | 12. SPONSORING MILITARY ACTIVITY<br>Air Force Cambridge Research Laboratories (CRD)<br>L.G. Hanscom Field, Bedford, Mass. 01730 |

13. ABSTRACT

The objective of this program is to evaluate the breakdown characteristics of selected microwave and VHF transmitting antennas under both ambient (cold air) and simulated reentry (plasma sheath including ablation effects) conditions at high altitude. The purpose of the program is to provide experimental data which will aid in selection of reentry jammers. The power-handling capabilities, the pattern of the radiated fields, and the input impedance of selected antennas which are compatible with the geometry of a conical reentry vehicle are to be determined.

The modifications of the basic test cone model to accomodate additional plasma diagnostic instrumentation are described and the results of measurements of the radiation pattern of the X-band slot antenna/model configuration under free-space and anechoic chamber conditions are presented. Tests of the microwave and diagnostic instrumentation in the plasma tunnel are described and the design/fabrication status of the VHF antenna electrical instrumentation is reported.

DD FORM 1 JAN 64 1473

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| 14. KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| Antenna Breakdown | | | | | | |
| Reentry Plasma Simulation | | | | | | |
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